# Electrostatic drive (ESD) results from GEO and application in Advanced LIGO T060015-00-K

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## 1 Purpose and references

This document presents a review of the electrostatic drives for Advanced LIGO. The main purpose is to ensure we are all making the same assumptions about ESD performance when designing loops, etc.

References:

Comments relating to the controls prototype electrostatic drive design LIGO-T060012-00-D.

Electrostatic drive plans: E040379-00-K.

Class. Quantum Grav. 19 (2002) 20392043 (AC bias suggestion).

## 2 GEO 600 ESDs

The GEO 600 drives are used with up to 650 V DC bias on one set of electrodes, and a smaller AC signal on the other set. Each drive consists of 4 electrode pairs. The drives are, nominally, 3 mm behind the test mass. During acquisition, when signals are large, the drive is linearised using an analogue square-root circuit. In-lock the signals are sufficiently small that this is not required, and is bypassed to reduce noise.

Each set of electrodes consists of interleaved conductor strips and gaps, both about 3 mm wide. The gold coating forming the pattern is quite thin (about 300 nm) and the tracks were kept 3 mm wide to keep the resistance reasonably low – typically about 5 Ω from an electrode to the mid-point of a 'finger' of the pattern. The damping due to this small resistance is negligible.

The drive calibration is known to better than 10% below 1 kHz and is $2.9 \times 10^{-13}$m/V at 100 Hz with 650 V bias (reference: Martin Hewitson, from GEO lab book). The suspension response at 100 Hz is modelled to beto $4.5 \times 10^{-7}$m/N, a few % accuracy. The force constant is therefore $6.4 \times 10^{-7}$N/V, with 650 V bias.

One way to characterise the drive is to write $F = \alpha V^2$, when $dF = 2\alpha V dV$. So $\alpha = 4.9 \times 10^{-10}$N/V$^2$.

## 3 Extrapolation to Advanced LIGO

The Advanced LIGO test masses are to be spaced 5 mm from the drive electrodes (baseline suspension conceptual design). This requires the gaps in the electrode pattern to be increased to about 5 mm to keep good drive efficiency (otherwise too many field lines close in front of the optic). The mirror is much larger than in GEO so the electrode pattern can be enlarged. This has been done for the controls prototype drive. The greater separation weakens the drive by roughly a factor of 2 (based on empirical results from a GEO-prototype and some early FE and Mathematica modelling for GEO). But this is nearly compensated by the increased area (the controls prototype ESD is effectively about double the area of those in GEO 600).

The controls prototype design was intended to be as flexible as possible, allowing wiring at the sides or top and bottom. It does not make maximum use of the available area[1]. The design is being reviewed for the noise prototype. The idea is to fill the permitted area of the reaction mass (i.e. that outside a central aperture of 95 mm radius) with a simplified electrode pattern. This allows an increase of about 35% in the force produced for a given voltage. The coupling coefficient should be $\alpha \approx 7 \times 10^{-10}\mathrm{N/V}^2$.

The 4-quadrant GEO design (4 separate signal electrodes and a set of 4 common 'bias' electrodes) is extended to include a separate low-coupling bias electrode. This may have anything up to about 10% of the coupling (capacitance) provided by the main set. The cost is a 20% increase in wiring and electronics. This extension has not yet been adopted as part of the baseline proposal. It increases the wiring needed from 5 to 6 wires, to obtain control in 3 degrees of freedom at two force levels each.

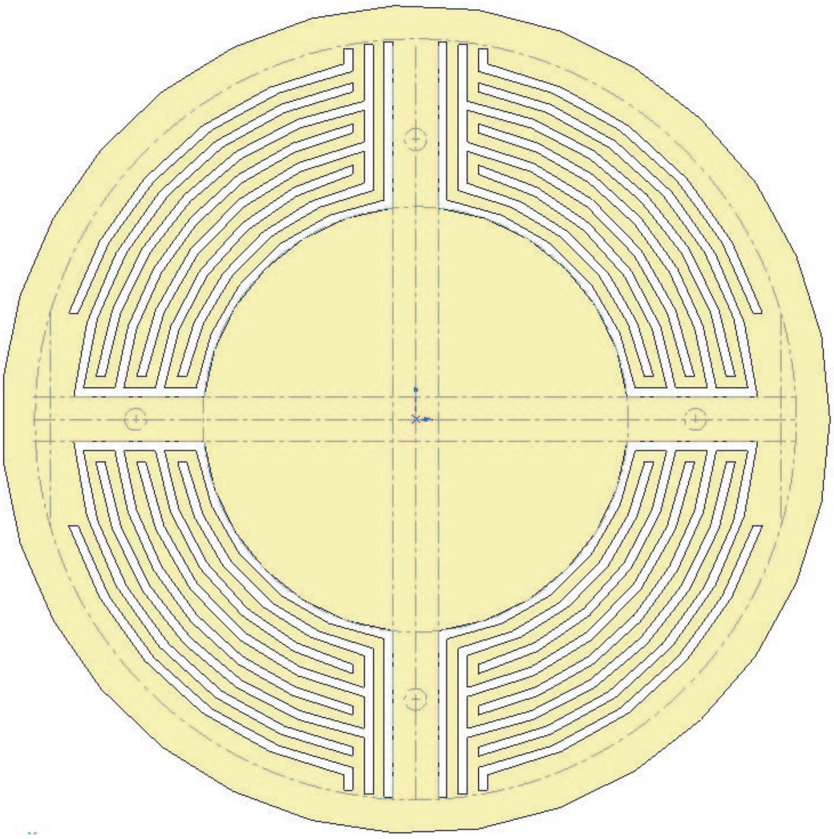

Figure 1: Initial drawing, by Russell Jones, of the proposed noise prototype ESD mask. The gold pattern is the inverse of the mask. The inner 190 mm diameter is reserved to transmit the beam and the outer dimension of the reaction mass can be observed as the faint line somewhat smaller than the mask – this to allow the mask to be supported during coating. The length of the new, outer electrodes remains TBD.

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[1] Document LIGO-T060012-00-D reports that the fabrication method employed for the controls prototype drive seems highly satisfactory. In particular it was possible to make acceptable connections, and the resistance of the gold pattern was quite small (around 1.5 Ω to the extreme points on the pattern). It, therefore, seems wise to continue to fabricate this way.

# 4 Driving the drives

It was assumed that, given the digital origin of all signals, all non-linear correction, bias generation etc. should be carried out in the digital domain. The baseline design would have 5 channels, for one common and 4 quadrants, which could be driven with any desired differential voltage to meet the requirements of various operating modes. This encourages digital generation of the optimum differential voltage ready for symmetrical amplification, allowing in-lock bias adjustment and even transition from DC to AC bias.

Flexibility can be further increased by providing two levels of gain, range, and output noise per channel so that asymmetrical drive arrangements – i.e. strong bias, weak signal – can be generated optimally with fixed DAC range, and reasonable noise requirements for signal transmission. It appears that the simplest way of doing this is just to switch the input resistor in what is, effectively, a standard inverting opamp stage. Differential inputs would be provided for both levels simultaneously, at the standard 10 V full-scale input range.

The (non-baseline) idea of adding a 6th electrode, common to the 4 quadrants but with perhaps 10–30 times weaker coupling should prove desirable, particularly for use in final science mode if there are no photon actuators, but possibly also for some of the intermediate commissioning stages.

There is a slight trade-off between adding the extra electrode and maximising the area of the main electrodes. Adjusting the width of the electrode strips to 4 mm allows a good compromise design (the gaps are be kept at 5 mm). The maximum coupling provided by the extra electrode is about 10% of that available from the main electrode pairs, but this can be decreased by shortening the electrodes.

The amplifiers, designed by Nick Lockerbie, provide 6 identical channels of amplification, each with differential inputs for low and high gain. The input noise is essentially flat over the band of interest, above 10 Hz, and so the driver stages may be characterised as follows.

| mode | max. v (Vpk) | gain | min. i/p ref. noise (100 Hz) $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ | dynamic range [1Hz] |
|---|---|---|---|---|
| high | 400 | 40 | 7 | 180 |
| low | 40 | 4 | 25 | 169 |

These noise figures are best-case, only for the driver stage, and system performance will be reduced by additional noise from input stage, whitening filters, and DACs.

It will probably be impractical to match the 180 dB dynamic range of the high-gain state to the smaller dynamic range of the DAC outputs. It is, however, much more likely that the 169 dB dynamic range of the low-gain state can be matched to the DACs, at least for final science-mode operation, with carefully designed whitening filters.

Provision of two levels of gain, and the two coupling-strengths at the ESD provides several different combinations of peak force and *rms* force-noise.

The maximum uni-polar force is calculated for the full end-to-end range of differential voltage (800 V with two channels at high gain, 80 V with two channels at low gain, and 80 V with 400 V bias when there is one at high gain and one at low gain). The force noise is $2\alpha V_\mathrm{b}\tilde{v}$, where $V_\mathrm{b}$ is the bias voltage, and it is assumed that the voltage on the other electrode consists only of noise voltage $\tilde{v}$, the true noise will be a little higher. The useable range probably half of the stated figure, if the drive is biased to half of maximum pull force.

- **A. Maximum force.** (Acquisition) Here the strong electrodes are used with maximum gain on bias and signal electrodes. Force range is $450\mu$N full-scale, noise is $2.2 \times 10^{-13}\mathrm{N}/\sqrt{\mathrm{Hz}}$.

- **B. Low signal gain, maximum bias.** Keeping the same bias, but driving the signal through a low gain channel provides a weaker drive. Force range 45 $\mu$N full-scale, noise is $5.6 \times 10^{-14}\mathrm{N}/\sqrt{\mathrm{Hz}}$.

- **C. Full gain, full bias, weak coupling.** Keeping the strong bias but using the weaker coupling electrode but keeping the signal gain large allows a weaker drive less susceptible to interference. Force range is up to 45 $\mu$N, noise is $2.2 \times 10^{-14}\mathrm{N}/\sqrt{\mathrm{Hz}}$. Can be weakened by shortening the weak electrode, if desired, which will reduce signal and noise by the same factor.
- **D. Weak drive.** A weak drive can be formed by applying signal with low gain and using the weak-coupling electrodes for bias, with high gain. Force range is up to 4.5 $\mu$N full-scale, noise is $5.6 \times 10^{-15}\mathrm{N}/\sqrt{\mathrm{Hz}}$.
- **E. Weakest drive.** A very weak drive can be formed by applying signal with low gain and using the weak-coupling electrodes for bias, with low gain. Force range is up to 450 nN full-scale, noise is $5.6 \times 10^{-16}\mathrm{N}/\sqrt{\mathrm{Hz}}$.

A crude LSC model (the one presented in T050267-00-K) suggests the force-displacement response of the test mass to actuator force noise (in loop) will be $\sim 3 \times 10^{-7}$ m/N around 100 Hz – assumed unity gain frequency for this loop – then falling off as expected. Taking this figure, and allowing the noise to reach 10% of the 100 Hz target sensitivity, suggests that the force noise can be up to $\approx 4 \times 10^{-15}\mathrm{N}/\sqrt{\mathrm{Hz}}$. This is to be confirmed using a more sophisticated representation of the LSC loop.

Option A. seems best suited to acquisition, option C. allows an approach towards design sensitivity while keeping good force range during commissioning, option E. should safely meet design requirements while offering peak force equal to that from a 68 W photon actuator.

The low-gain drive yields about 10 dB less dynamic range than the high-gain case (because the maximum power dissipation in the feedback resistor of the inverting circuit is 10 dB less than in the high gain case). Note, however, that by selecting the 'input' resistor any gain level between the low and high values shown in the illustration can be obtained with corresponding intermediate values of dynamic range. The feedback resistor is fixed at 100 k$\Omega$ for technical reasons.

## 5 Comment on bias waveform

At some point in the development of ESDs within GEO there was encouragement from Mitrofanov et al (Class. Quantum Grav. 19 (2002) 20392043) to try AC bias (based on some results from a torsion pendulum experiment at MSU). We have not explored this option, and have no immediate plans to do so. The motivation to try AC bias could arise at any time, but its necessity will not likely be determined before implementation on Advanced LIGO. This led us to design amplifiers that could cope with any practical AC bias (16384 Hz would be the worst case, motivated by reduction of aliasing – of course much lower frequencies should also be considered). AC bias is probably only required for science mode, if at all. It may be possible to use quite small bias voltages in science mode, when our design will be found to have been very conservatively rated. The adoption of water cooling (needed to remove several watts of quiescent power) renders this issue relatively unimportant.